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TITLE ANTHEM SIMULATION OF THE EARLY TIME MAGNETIC FIELD PENETRATION OF THE PLASMA SURROUNDING A HIGH DENSITY Z-PINCH

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ABSTRACT

The early time penetration of magnetic field into the low density coronal plasma of a Z-pinch fiber is studied with the implicit plasma simulation code ANTHEM. Calculations show the emission of electrons from the cathode, pinching of the electron flow, magnetic insulation of the electrons near the anode, and low density ion blow off. PIC-particle ion calculations show a late time clumping of the ion density not seen with a fluid ion treatment.

INTRODUCTION

A high density Z pinch can consist simply of a fiber connecting a solid cathode at one end to a solid anode at the other. From a Marx system a drive voltage is applied from anode to cathode across this system. The fiber is typically 10^{-3} cm in radius; it has been made of plastic or, recently, extruded deuterium ice. By some complex process, possibly field emission of electrons from the cathode breakdown of the insulating fiber rapidly proceeds. It becomes a plasma. MHD calculations[1] indicate that, 35 ns after the voltage is applied, this plasma expands to a radius of 0.1 to 0.3 cm, surrounding a 5 cm long fiber. Beyond 0.15 cm the plasma electron density drops rapidly below 10^{17} cm^{-3}. In experiments at Los Alamos the resultant current in the fiber rose nearly linearly over 130 ns to a level of 0.25 MA. If all the current at 35 ns is inside a radius of 0.15 cm, this corresponds to a magnetic field of 8.9 T at that radius. Beyond this radius the plasma conditions are not unlike those encountered in high density plasma opening switches (POS)[2], where a rapidly rising (60 to 500 ns time scale) magnetic field (from 0.8 to 3.0 T) penetrates a 10^{15} to 10^{16} cm^{-3} plasma through a combination of erosive, $E \times B$ drift, and MHD mechanisms.

We have applied the ANTHEM[3] implicit simulation model to the study of field penetration of the low density plasma surrounding the Z pinch fiber. The retention of electron inertia, and the inclusion of relativistic effects in the code allow us to study the run away of electrons in the low density sheath, without the imposition of arbitrary low density cut offs required with MHD and hybrid models. The code's implicit treatment of the electric and magnetic fields allow us to model the global system with computational cells much larger than a Debye length, and using time steps much longer than a plasma period (going well beyond the usual constraints of PIC codes).

The present results are preliminary and limited to an examination of the early time field penetration through the low density plasma regions. We examine the emission of electrons at the cathode, their erosion and pinching at that electrode, and their magnetic insulation at the anode. We also note a clumping effect in the ions, seen only when they are modeled as PIC particles.

THE MODEL

Calculations were performed with the ANTHEM implicit simulation code[3]. This is a multi-fluid/PIC model. For its present application separate electron and ion fluids were employed to represent the background electrons and ions constituting the fill plasma, and a third electron fluid was introduced to model the emission. The solution for electric and magnetic fields is obtained implicitly from Maxwell's equations by the Implicit Moment Method[3,4]. Thus, the electric and magnetic fields are advanced by

$$E^{m+1} = E^{(m)} - 4\pi c\Delta t j^{(m+1)} + c\Delta t\nabla \times B^{(m+1)}$$

$$B^{(m+1)} = B^{(m)} - c\Delta t\nabla \times E^{(m+1)}$$

with time-advanced currents, $j^{(m+1)} = j[E^{(m+1)}]$, determined from a set of auxiliary moment equations. In our simulations the $v \times B$ term was treated implicitly[3]. For the present results plasma resistivity was set to zero.

Substitution of the expression for auxiliary currents into the Ampere's law gives an elliptic equation for a single azimuthal component of magnetic field B_θ in the cylindrical geometry, when only radial and axial plasma motion is permitted. This is solved with a Chebycheff solver requiring 0.02 sec/solve for a 50 x 50 mesh. Given the B field, we obtain E from the Ampere's law and the auxiliary moment equation for j. The plasma properties are then advanced in these fields. With particle modeling we simply update Newton's equations. For fluid modeled components the properties are advanced in two stages. In the first, Lagrangian stage velocities for the cell walls confining the fluid elements are first obtained, and the walls are moved. In the second, Eulerian stage the walls are shifted back to their original positions and fluid moves across. Van Leer corrections are applied at this juncture to achieve nearly second order spatial differencing with stability. After the plasma updates the resultant true currents are compared to the approximate currents predicted with the field solution. The deviation between these two currents is used to generate a correction to the E field calculated in the next cycle. This correction term is crucial in maintaining near quasi neutrality in dense regions of the pinch plasma. Since the writing of Ref. 3, changes have been made to base the model on momenta rather than velocities, so that electron relativistic effects are included.

FIELD PENETRATION RESULTS

For the Z pinch simulations we assumed a 10^{14} cm^{-3} plasma. A low emission threshold (30 V/cm) for electrons was selected. A sketch representing the Z pinch load is shown in Fig. 1.

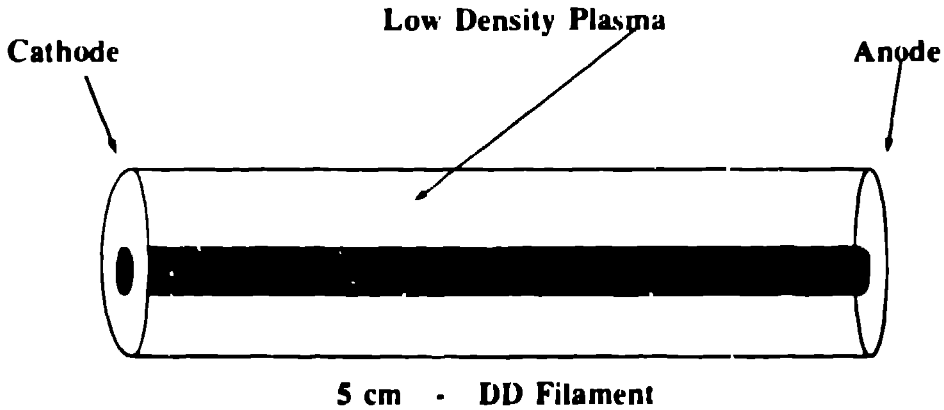

Fig. 1

We applied a constant 1 MV drive voltage and employed a 50 nH generator inductance, so that the characteristic rise time to a 1 MA drive current through the pinch was 50 ns. We assumed an inner dense plasma out to 0.1 cm radius with 20 Ohms resistance. The outer edge of this plasma was made the lower boundary of our computational region. So, the 20 Ohm fiber resistance was treated as an axial load by the code.

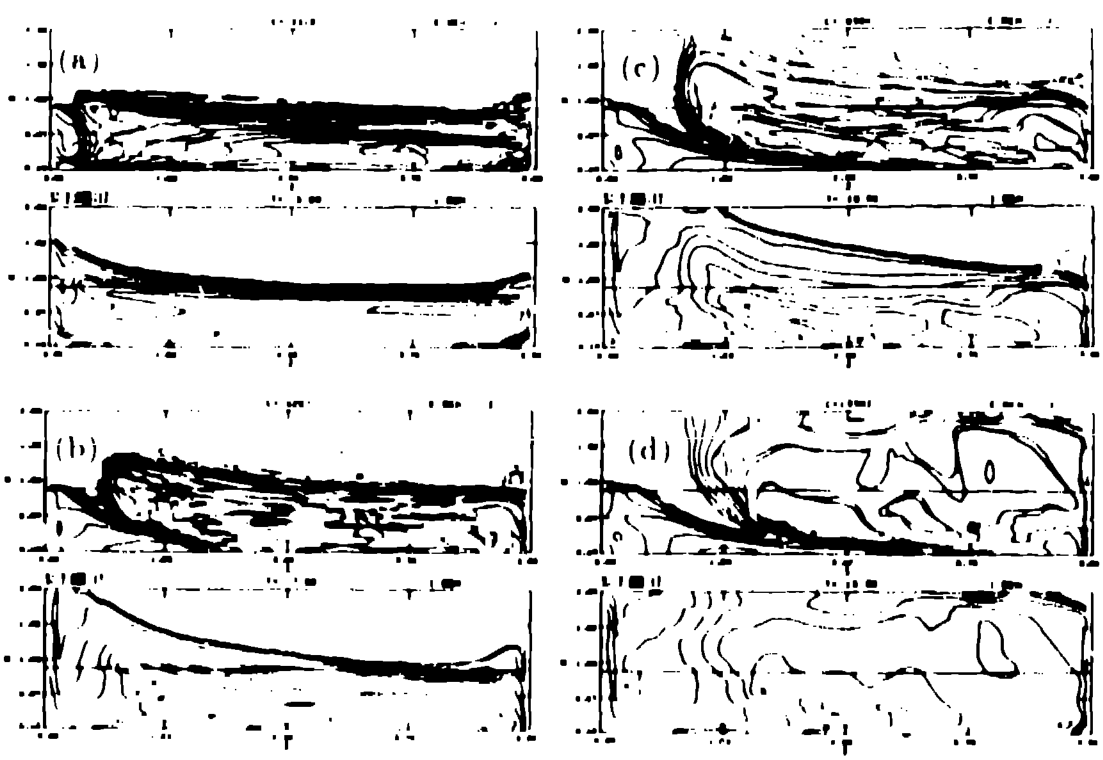

Fig. 2

Figure 2 collects early time history for the calculated evolving coronal electron and ion densities in the Z-pinch. The frames (a-d) are for t = 5, 7.5, 10 and 15 ns, respectively. The four fames reflect the first 15 ns of pulse rise. For the coronal plasma we assumed an initial density of 10^{14} electrons/cm^3, extending beyond the dense fiber at r = 0.1 cm (lower boundary) out to 1.0 cm. The top subfigure in each frame shows a set of density contours for the emitted electrons flowing from the cathode (on the left) and the background electrons. Each bottom subfigure shows the evolving ion density contours.

Starting at 5 ns a gap in the electron density is evident near the cathode. The emitted electron stream pinches toward the axis, so that by 15 ns it squeezes down to less than 0.2 cm. Significant ion blow-off is evident by 7.5 ns. This is most pronounced near the cathode. We also see a tendency for the electrons to pinch toward the axis near the anode, a magnetic insulation effect also seen in POS switches[2].

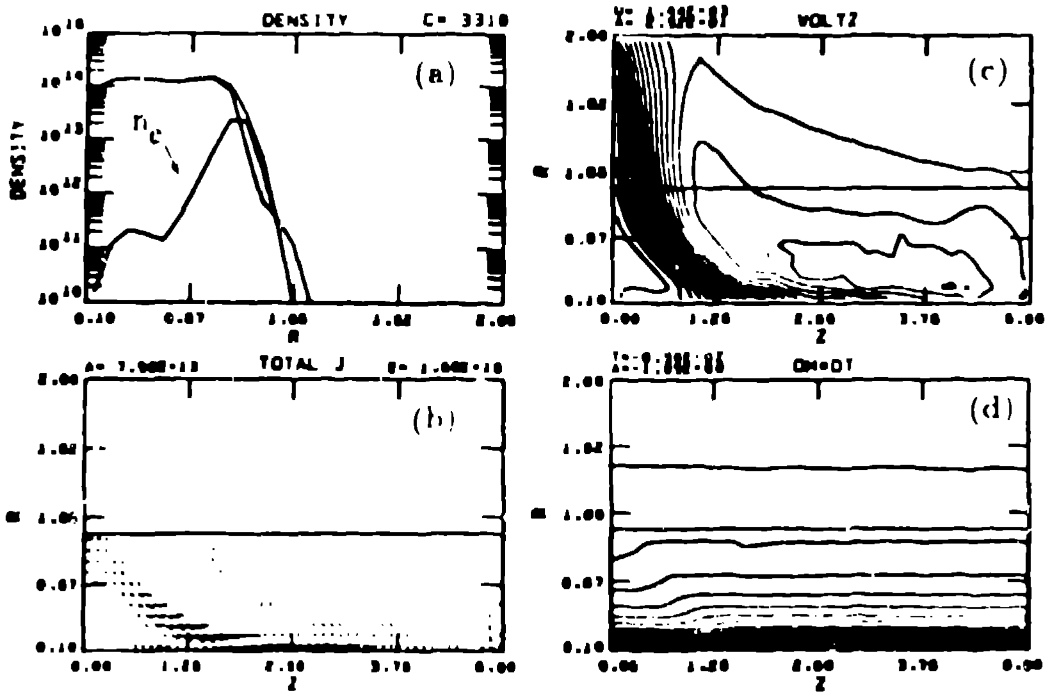

Fig. 3

Figure 3 (a) above shows a cross section of the pinch densities at the cathode at 5 ns. The emitted electrons of density n_e principally populate the larger radii near r = 1 cm. The remaining frames are for 15 ns. In frame (b) we see that the electron flux vectors (opposite the current) are pinched toward the axis. The voltage (c) runs from 0 to a 1.44 MV maximum, with most of the change occurring across the current sheet near the cathode. The magnetic field (d) is maximum along the inner rod, but strongly perturbed by the emission current sheet.

The fluid treatment of ions may be unrealistic due to its inability to model finite ion gyro effects. ANTHEM allows for particle ion modeling, but we have limited experience with its use. Figure 4 shows results for the Z-pinch run with particle ions. The times shown are (a-d) t = 2.5, 4.5, 5.5 and 7 ns. Electron density contours are shown in the top subframe at each time, and the ion particles are plotted in the lower subframe. From the quiet initial start, with 1 eV ions we find that the rising, penetrating B field bunches the ions near the low density plasma edge by 4.5 ns, and leads to significant clumping throughout the plasma by 7 ns. Work is continuing to determine the significance of the finding.

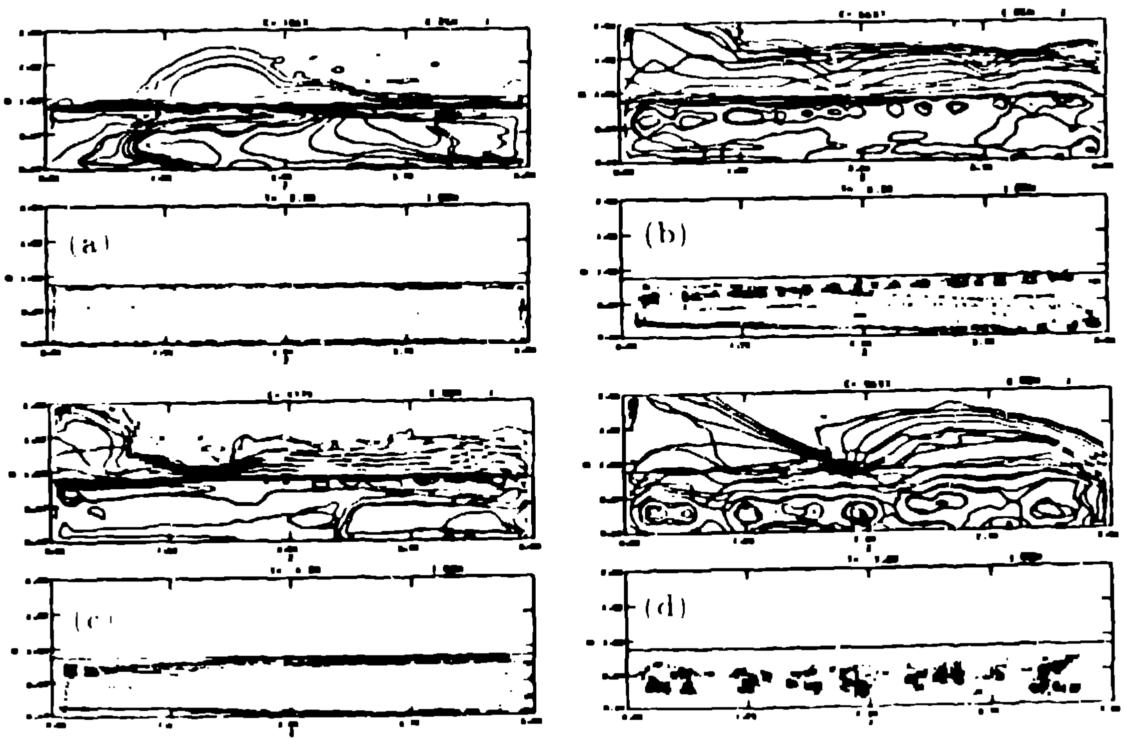

Fig. 4

CONCLUSIONS

The ANTHEM model has been used in a preliminary study of the penetration of magnetic field into the low density (10^{14} electrons/cm^3) plasma surrounding a Z pinch. Several effects characteristic of POS plasmas have been seen in the Z pinch dynamics. An erosion like gap in the plasma density rapidly forms near the cathode. The cylindrical geometry then leads to pinching of the electron current sheet associated with the formation of this gap. Magnetic insulation is also found prohibit direct entry of the electrons into the anode at large radii, and encourages pinching of the electron flow near this electrode. When ion particle modeling is employed a rapid clumping of the ions is in evidence, which may indicate instability due to finite ion gyro radii effects. Further scrutiny of this is warranted.

ANTHEM possesses an option to model deposition of the emitted electrons on a denser background fluid. Thus, a reasonable extension of this work would be to include the denser fiber plasma as background extending out from the centerline. Effects such as direct heating from collisions of the emission plasma on the fiber could then be examined.

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